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14. ABSTRACT

The focus of this program is fundamental research in general methods of analysis and design of complex uncertain nonlinear systems. The approach builds on our recent success in blending robust and nonlinear control methods with a much greater emphasis on the use of local and global techniques in nonlinear dynamical systems theory. Specific areas of accomplishment include real-time trajectory generation for unmanned aerial vehicles, geometric mechanics and nonlinear stabilization, linear parameter varying control, and unified techniques for stabilization of nonlinear systems that combine model predictive control techniques with control Lyapunov function techniques. In addition, the program explored techniques for modeling and control of chemically reacting systems, with applications to gas turbine engines and materials growth.

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ROBUST NONLINEAR CONTROL THEORY WITH APPLICATIONS TO AEROSPACE VEHICLES

AFOSR-PRET GRANT F49620-95-1-0419

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Final Report
15 June 1995 to 14 June 2000

1 Objectives

The focus of this program is fundamental research in general methods of analysis and design of complex uncertain nonlinear systems. Our approach builds on our recent success in blending robust and nonlinear control methods with a much greater emphasis on the use of local and global techniques in nonlinear dynamical systems theory. Specific areas of interest include real-time trajectory generation for unmanned aerial vehicles, geometric mechanics and nonlinear stabilization, and unified techniques for stabilization of nonlinear systems that combine model predictive control techniques with control Lyapunov function techniques. In addition, we are exploring techniques for modeling and control of chemically reacting systems, with applications to gas turbine engines and materials growth.

2 Status of Effort

This activity is now complete. The program has developed new theory and tools for nonlinear control, including a unified approach to nonlinear stabilization that combines model predictive control (MPC) with control Lypaunov functions (CLFs), new results in nonlinear control of mechanical sytems, and applications of linear parameter varying control to aerospace systems. The results of the program are described in detail on the project homepage:

`http://www.cds.caltech.edu/~murray/projects/afosr95-vehicles/`

3 Accomplishments

In this section we give a brief summary of the major accomplishments of the program. Details can be found in the references and on the project homepage.

3.1 Unified Approach to Nonlinear Stabilization

One of the major accomplishments of the program was the develpoment of Model Predictive Control (MPC) strategies for the stabilization and maneuvering of flight vehicles. Model based approaches hold forth the possibility of higher performance operations through the understanding and exploitation of system nonlinearities including control saturations.

Most MPC strategies derive from the fact that stabilizing controllers may be constructed through the use of optimal control. In a number of interesting cases, e.g., the linear quadratic regulator, "solutions" to optimal problems of interest can be found and implemented—the calculations are practicable and the solution has a manageable representation. Unfortunately, the curse of dimensionality adversely impacts the calculation *and* representation of optimal feedbacks when significant nonlinearities are present.

One way to resolve the representation problem is to use on-line calculations (rather than off-line) to provide the necessary optimal feedback. A typical strategy is to solve, at each time (or in sampled data fashion), a finite horizon trajectory optimization problem to obtain the desired control as a function of the current state. Of course, one must ensure that the resulting receding horizon control strategy results in a stable closed loop system. This is especially important in the control of high performance flight vehicles which are often designed with maneuvering, and not stability, in mind. (In contrast, stability has not been a primary issue in the successful application of MPC to a number of open loop stable industrial chemical processes.)

Over the past several years, we have developed provably stable techniques that combine receding horizon control with control Lyapunov functions and allow excellent performance even when very short horizons are used for the online optimization. Over the past year, we have focused on providing theoretical and algorithmic improvements required to implement these systems on engineering platforms, using the Caltech ducted fan as a prototype.

A key element of the approach, developed under prior PRET funding, was to show that the end point constraints that are typically present in MPC approaches can be converted to a terminal cost that is based on the value of a CLF. This greatly simplifies the finite time optimization problem to be solved and is a key element in enabling real-time implementation.

In work jointly sponsored by DARPA, we have derived new theoretical results that demonstrate that incremental improvements during iterations of the algorithm are sufficient to guarantee stability for receding horizon control techniques [9]. This provides a solid framework for implementing algorithms that use a finite number of iterations at each step of the algorithm.

We have also implemented a real-time algorithm for trajectory generation in the presence of state and input constraints, based on combining ideas from differential flatness and collocation to obtain high performance algorithms. This approach has been demonstrated on simulations of the Caltech ducted fan and timing results indicate they can be implemented on the experimental system [11].

This work is being continued as part of the DARPA-sponsored Software Enabled Control (SEC) program and involves several industrial partners.

3.2 Linear Parameter Varying Control and Its Applications (UMN)

In work initiated under the PRET program in 1998, UMN has been working on the design of vibration attenuation controllers for the ACTEX satellite. ACTEX is cooperative program between AFRL/Space Vehicles Technology Directorate, Ballistic Missile Defense Organization (BMDO) and TRW Inc., to demonstrated vibration suppression of a pointing platform in space. The main objective of the ACTEX flight experiment is to demonstrate the space-readiness of embedded PZT

sensors and actuators for system identification and structural control. In past years, we have developed a model of the ACTEX structure based on experiment data from space tests and have developed controllers for our model.

The vibration attenuation controllers we designed for the ACTEX satellite have been tested in space by TRW. These controllers performed better than open-loop in parts of the frequency domain and worse than open-loop in other frequency ranges. Our analysis indicates that these controllers were implemented with an incorrect sign. Therefore, TRW plans to re-uplinked these controllers with the correct sign to the ACTEX satellite and send us the on-orbit experimental results.

In the area of linear parameter varying systems, the results of our research under the AFOSR PRET program has led to three new research programs at UMN. A direct out growth of our work under the AFOSR PRET program is funding from NASA Dryden to synthesize a LPV controller for the F-18 Systems Research Aircraft (SRA) in the up-and-away flight regime. The objective is take this design from nonlinear simulations to pilot-in-the-loop simulations and then to flight test.

To date we have synthesized longitudinal and lateral-axis LPV controllers for the Class B flight envelope of the F/A-18 SRA. Pilot in the loop simulations are scheduled for August 2000. Upon a successful completion of piloted simulation, the next stage is to code these LPV controllers in Ada and implement them in the PSFCC research computer and test them in hardware in the loop simulations. Flight tests are planned for Spring 2001.

A second program which has started as an outgrowth of our PRET research is part of the NASA Aviation Safety Program, entitled "Application of Linear Parameter-Varying Techniques to Safety Critical Aircraft Flight Systems." It is being funded by NASA Langley under the NASA Safety Program. Under this program we plan to develop a unified approach to health management and control under adverse flight conditions using linear, parameter-varying (LPV) system theory.

Finally, we have funding from DARPA under the Software Enabled Control program to develop theory, algorithms and software modules required to perform inner-loop vehicle control, trajectory generation for rapid tactical response and vehicle system management for an unmanned combat air vehicle. The goal is a complete, unified design framework to synthesize and simulate individual vehicle management systems. All of these research programs build on the LPV control foundation developed under the AFOSR PRET program.

3.3 Dynamics and Control of Mechanical Systems

Motivated by problems in formation flight for micro-satellite clusters, we have continued our work in nonlinear control of mechanical systems by exploring the use of geometric structure in optimal control problems. This is relevant for satellites since their dynamics are dominated by Lagrangian structure and there is a critical need to exploit this structure to minimize fuel usage.

Over the past year, we have investigated the optimal control of affine connection control systems and achieved some initial results [6]. The formalism of the affine connection can be used to describe geometrically the dynamics of mechanical systems, including those with nonholonomic constraints. In the standard variational approach to such problems, one converts an n dimensional second order system into a $2n$ dimensional first order system, and uses these equations as constraints on the optimization. An alternative approach, which we develop in the referenced paper, is to include the system dynamics as second order constraints of the optimization, and optimize relative to variations in the configuration space. Using the affine connection, its associated tensors, and the notion of covariant differentiation, we show how variations in the configuration space induce variations in the tangent space. In this setting, we derive second order equations have a geometric formulation parallel to that of the system dynamics. They also specialize to results found in the literature.

We have also considered the optimal control of time-scalable systems [5]. The time-scaling property is shown to convert the PDE associated with the Hamilton-Jacobi-Bellman (HJB) equation to a purely spatial PDE. Solution of this PDE yields the value function at a fixed time, and that solution can be scaled to find the value function at any point in time. Furthermore, in certain cases the unscaled control law stabilizes the system, and the unscaled value function acts as a Lyapunov function for that system. For the example of the nonholonomic integrator, this PDE is solved, and the resulting optimal trajectories coincide with the known solution to that problem.

Past theoretical work that has been performed in this area forms a central part of a variety of new programs. Under AFOSR funding, we have a program to explore specific problems associated with the dynamics and control of micro-satellite clusters (see report in this volume) and we have also developed several collaborative efforts with the Jet Propulsion Laboratory (JPL) for deep space missions. In addition, the work in nonlinear control of mechanical systems is part of two new MURI proposals that are based on some of the fundamental work performed under this program.

3.4 Integrated modeling, identification, analysis, and design.

The use of mathematical models to design large systems involves various instances and possibly iterations of modeling, identification, system design and controller synthesis, and various forms of analysis and simulation. We are developing a variety of techniques for attacking individual problems as well as integration of these problems.

- New techniques have been developed for modeling of white noise by employing standard statistical tests in order to identify a typical set, and performing subsequent analysis in a worst-case setting. The combination of white noise and unmodeled dynamics allows a solution to the the robust $\mathcal{H}_2$ performance problem, which is rooted in the origins of robust control theory.

- The $\mathcal{H}_\infty$ framework was extended in [1] and [2] to allow for general performance constraints when designing controllers in an l_2 setting. Some of these extensions include synthesizing controllers for systems subject to a mix of arbitrary l_2 disturbances and deterministic noise disturbances [3], and the synthesis of controllers for plants subject to full structured uncertainty [1]. These results can in turn be combined with other linear matrix inequality based solutions, such as the linear parameter varying framework [4].

- A numerically efficient algorithm has been developed for providing a lower bound on robust performance of a nonlinear system along a prespecified trajectory [13]. This algorithm has been applied to an F16 model and indicates high potential for robustness analysis of this type.

- Developed a technique to compute upper bounds on robust performance by approximating a nonlinear system by a rational system which can be represented using linear fractional transformations [12]. Initial testing indicates that this approach has poor growth characteristics and hence is computationally difficult.

- We have developed robust simulation theory and code for discrete time nonlinear systems. Robust simulation allows one to simulate all possible trajectories for a nonlinear system. By simulating all trajectories, one can obtain upper bounds on worst case nonlinear performance [10].

3.5 Trajectory Generation and Tracking Using Differential Flatness

Murray and his coworkers have been investigating techniques for online trajectory generation for flight control applications, motivated by problems in uninhabited aerial vehicles. The role of trajectory generation is important in these systems since the pilot is not in the plane and therefore cannot provide feasible guidance commands in highly aggressive flight situations. We are investigating techniques for generating state and input trajectories which satisfy the equations of motion and trade off tracking performance for internal stability. Currently we are not explicitly considering actuator constraints (magnitude and rate limits), although we believe that the theory can be extended to handle this case along the lines of the techniques proposed here.

The results to date in this area include the development of real-time algorithms for trajectory generation and application of those algorithms to a small flight control experiment at Caltech. Results on the experiment demonstrate the value of performing real-time trajectory generation for situations in which the desired vehicle position is specified in real time (via a joystick) and there is a clear increase in performance over standard linear techniques.

We have also derived conditions for checking differential flatness for different classes of nonlinear mechanical systems. In particular, for simple mechanical systems (kinetic plus potential energy) with one fewer input that configuration variable, we have given necessary and sufficient conditions for a system to be flat in terms of the covariant derivatives of certain objects determined from the way in which external forces enter the system.

3.6 Numerical Algorithms for Analysis and Design of Nonlinear Control Systems

We continue to develop software tools for robustness analysis of nonlinear systems. Our original work in this area (with J. Tierno, now at Honeywell) considered the problem of worst case analysis of a nonlinear system along a give trajectory. Although local in nature, the techniques provided the ability to incorporate noise, uncertainty in initial conditions, (real) parametric uncertainty, and a class of unmodeled dynamics. The information provided by this numerical tool complements the more traditional Monte Carlo approach for analyzing robust performance of a system.

In the past 24 months, we have developed some efficient algorithms for verifying the stability of uncertain discrete time piecewise linear systems. While piecewise linear systems are intuitively simple, they are computationally hard. Two approaches to verifying stability are presented. For each approach, separate necessary and sufficient conditions are given. The first approach requires the solution of a linear matrix inequality. This method is only applicable to a restricted class of piecewise linear systems, and is generally very conservative. It is demonstrated that for most piecewise linear systems, these conditions yield no information. The second, more general, approach is based upon robust simulation. This method is useful for all piecewise linear systems, and will always yield a definitive answer. If a system initially satisfies necessity, but fails sufficiency, these algorithms can be systematically refined and after a finite number of refinements, a definitive answer is guaranteed.

In the past 6 months, we have begun to develop new software for design of nonlinear control systems. This software represents a nonlinear system by a collection of Taylor series representations of arbitrary order at a given set of points. By using multiple local approximations, we are able to better represent nonlinear function in a way which is computationally tractable and fits with current nonlinear identification techniques (which include table lookups and linearizations about operating points). An initial library of routines has been created which allows standard operations such as Lie brackets and involutivity checks. Future work will concentrate on computation of

(approximately) flat outputs for nonlinear systems.

3.7 Dynamics and Control of Chemically Reacting Systems

For several years, in conjunction with the AFOSR PRET on Aeroengines, we have been exploring the use of dynamics and control techniques for modeling and control of chemically reacting systems. The primary application in past work has been combustion instabilities, which was pursued in collaboration with United Technologies Research Center. Over the past year, we have shifted the focus to a different chemically reacting system, namely materials processing and growth of thin films. This work is jointly sponsored by DARPA and NSF as part of the Virtual Integrated Prototyping (VIP) program, with the emphasis in this program being on developing new control-oriented modeling techniques.

The system that we are studying is a MOCVD reactor for growth of YBCO super-conducting thin films. We have developed a Monte Carlo model of the system and have been using this model to explore the response of the system to time-varying growth conditions. We vary temperature and partial pressure sinusoidally and identify behavior typical of low-dimensional nonlinear systems. In particular, the frequency content of the roughness response is sensitive to the presence of steps in the surface, indicating some low dimensional nonlinear effects might be present [8].

For closed-loop control of thin film deposition, one would like to directly control film properties such as roughness, stress, or composition, rather than process parameters like temperatures and flow rates. This requires a model of the dynamic response of film properties to changes in process conditions. Direct atomistic simulation is far too slow to be used in this capacity, but a promising approach we explore here is to derive reduced-order dynamic models from atomistic simulations.

In [7] we consider film growth on a vicinal surface using a kinetic Monte Carlo model. The temperature range spans the transition from smooth step flow to rough island growth. Proper Orthogonal Decomposition is used to extract the dominant spatial modes from the KMC simulations. Only five spatial modes adequately represent the roughness dynamics for all simulated times and temperatures, indicating that a 5-state model may be sufficient for real-time roughness control.

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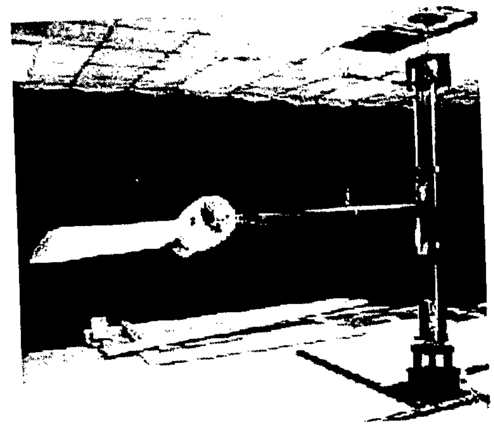
Robust Nonlinear Control Theory with Applications to Aerospace Vehicles



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Blaise Morton
Honeywell Technology Center

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Overview	Papers	People	Transitions	More Info

Project Overview

The focus of this program was on fundamental research in general methods of analysis and design of complex uncertain nonlinear systems. Our approach built on our successes in blending robust and nonlinear control methods,
with a much greater emphasis on the use of local and global techniques in nonlinear dynamical systems theory. Specific areas of interest included real-time trajectory generation for unmanned aerial vehicles, geometric
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Papers and Presentations

Technical papers [Index, Search]

Selected archival papers describing some of the work in this project:

- Heteroclinic connections between periodic orbits and resonance transitions in celestial mechanics
- Nonlinear Optimal Control: A Control Lyapunov Function and Receding Horizon Perspective
- Real Time Trajectory Generation for Differentially Flat Systems
- Numerically Efficient Robustness Analysis of Trajectory Tracking for Nonlinear System
- Optimally scaled H_inf full information control with real uncertainty: Theory and application
- A Testbed for Nonlinear Flight Control Techniques: The Caltech Ducted Fan

For a more complete list, see the publication index or search for a specific publication.

Project reports and presentations

- Annual reports (PDF): 1996, 1997, 1998, 1999, 2000, Final
- Summary presentations (PDF): 1996, 1997, 1998, 1999, 2000
- Killer charts (PDF): 1997, 1998, 1999, 2000
- AASERT awards
  - 61063 (1996, LPV-UMN): 1996, 1997, 1998, Final
  - 61051 (1997; trajgen): 1997, 1998, 1999, 2000
  - 61492 (1998; NL tools): 1998, 1999, 2000

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People

The following individuals were supported or partially supported by this award:

Faculty and senior researchers

- Richard M. Murray (Caltech) - Professor and Principal Investigator
- John C. Doyle (Caltech) - Professor and Co-Investigator
- Jerrold E. Marsden (Caltech) - Professor and Co-Investigator
- Gary Balas (U. Minnesota) - Professor and Co-Investigator
- Sunil Agrawal (U. Delaware) - Visiting Professor at Caltech, 1997-1998
- John E. Hauser (U. Colorado) - Visiting Professor at Caltech, 1998-1999
- David Chichka (Caltech/UCLA) - Research Associate, 1995-2000
- Sanjay Lall (Caltech) - Postdoctoral Scholar and Research Engineering, 1996-2000

Postdoctoral Scholars

- Brianno Coller, Caltech, 1996-97
- Geir Dullerud, Caltech, 1995-96
- Ian Fialho, UMN, 1998-99
- Sameer Jalnapurkar, Caltech, 1998-2000
- Wang Sang Koon, Caltech, 1997-98
- Banavara Sashikanth, Caltech, 1997-2000
- Willem Sluis, Caltech, 1995-96

Graduate Students

- Carolyn Beck, Caltech, 1995-96
- Raktim Bhattacharya, UMN, 1998-2000
- Anthony Blaom, Caltech, 1995-98
- Francesco Bullo, Caltech, 1996-98
- Dong-Eui Chang, Caltech, 1998-99
- Raffaello D'Andrea, Caltech, 1995-97
- Jeremy Dillon, Caltech, 1997-98
- Alex Fax, Caltech, 1996-2000
- Xiaolin Feng, Caltech, 1995-97
- Martha Gallivan, Caltech, 1997-2000
- Suvo Ganguli, UMN, 1999-2000
- Sonja Glavaski, Caltech, 1995-98
- Yun Huang, Caltech, 1995-99
- Michael Kanter, Caltech, 1995-97
- Sven Khatri, Caltech, 1995-97
- Rick Lind, UMN, 1995-96
- Mark Milam, Caltech, 1995-2000
- John Morris, Caltech, 1995-96
- Volkan Nalbantoglu, UMN, 1997-1998
- Matthew Newlin, Caltech, 1995-96
- Michiel van Nieuwstadt, Caltech, 1995-96
- Fernando Paganini, Caltech, 1995-96
- Pablo Parrilo, Caltech, 1997-1998
- James Primbs, Caltech, 1998-1999
- Jong-Yeob Shin, UMN, 1997-1998
- Peter Thomson, UMN, 1995-96
- Matthew West, Caltech, 1999-2000
- Jie Yu, Caltech, 1999-2000
- Xiaoyun Zhu, Caltech, 1995-2000

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Transitions

Government and industry interactions [Index, Search]

Over the course of the program, many companies and government labs have been involved in the work of the center. Click on the links below for more information about the nature of the interactions and transitions:

- 3M
- Applied Physics Laboratory
- Boeing (North American)
- Honeywell
- Jet Propulsion Laboratory
- Lockheed Martin
- MuSyn, Inc
- NASA Langley Research Center
- Naval Air Warfare Center
- United Technologies Research Center

For a more complete list, see the transitions index or search for a specific activity.

Software

The following software has been developed as part of this program. Highlighted links are available for download. For other software, please contact Richard Murray.

- LIBTG - trajectory generation library for differentially flat systems
- Worst - a matlab package for worst case analysis of nonlinear systems along trajectories
- DFA - discrete function approximation, a nonlinear control analysis and design package
- NTG - nonlinear trajectory generation package

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Additional Information

Continuing activities: projects that have continued the work started in this program

- Formation Flight for Micro-Satellites (AFOSR)
- High Confidence Reconfigurable Distributed Control (DARPA SEC)
- Multi-Vehicle, Wireless Testbed for Networked Control, Communications, and Computing (AFOSR)

Related web resources

- Caltech Control and Dynamical Systems
- Ducted Fan Homepage (somewhat out of date)
- Administrative Information (authorized users only)
- Archive of Aircraft Simulation Models (warning: incomplete and not well documented)

[top]	Overview	Papers	People	Transitions

Richard Murray (murray@indra.caltech.edu)

Vehicles Preprint Archive

Papers are listed in reverse chronological order (more or less).

This is a searchable database. Enter keywords below and press return to perform a search.

Keywords: Search

More detailed search

00c/fam00-gnc
: Differentially Flat Systems with Inequality Constraints: An Approach to Real-Time Feasible Trajectory Generation
Nadim Faiz, Sunil Agrawal and Richard Murray
To appear, *J. Guidance, Navigation and Control*, 2000

00a/klmr00-chaos
: Heteroclinic connections between periodic orbits and resonance transitions in celestial mechanics
W. S. Koon, M. Lo, J. E. Marsden, and S. Ross
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: Finite-Horizon Optimal Control and Stabilization of Time-Scalable Systems
Alex Fax and Richard Murray
2000 Conference on Decision and Control

99a/pnd99-ajc
: Nonlinear Optimal Control: A Control Lyapunov Function and Receding Horizon Perspective
J. A. Primbs, V. Nevisti□c, and J. C. Doyle
Asian Journal of Control, 1(1):1-11, 1999

98p/fhm99-cca
: Robustness Analysis of Accelerometry Using an Electrostatically Suspended Gyroscope
J. Alex Fax, Daniel A. Hill, and Richard M. Murray
1999 IEEE Conference on Controls Applications

98n/mm99-cca
: A Testbed for Nonlinear Flight Control Techniques: The Caltech Ducted Fan
Mark Milam and Richard M. Murray
1999 Conference on Control Applications

98h/gmm98-cdc
: Model Reduction via Centering and Karhunen Loeve Expansion
Sonja Glavaski, Jerrold E. Marsden, Richard M. Murray
1998 Conference on Decision and Control

98d/rm98-cdc
Discrete Function Approximation: Numerical Tools for Nonlinear Control
Muruhan Rathinam and Richard Murray
1998 Conference on Decision and Control

98a/zbm98-dss
The energy momentum method for the stability of nonholonomic systems
D. V. Zenkov, A. M. Block, and J. E. Marsden
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98a/jm99-rcd
Stabilization of relative equilibria ii
S. M. Jalnapurkar and J. E. Marsden
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98a/ggm98-cca
A Design Study for Thermal Control of a CVD Reactor for YBCO
Martha Gallivan, David Goodwin, and Richard M. Murray
1998 Conference on Control Applications

97m/nm97-ecc
Outer flatness: trajectory generation for a model helicopter
Michiel van Nieuwstadt and Richard M. Murray
1997 European Control Conference

97d/lm97-physd
Stability and drift of underwater vehicle dynamics: Mechanical systems with rigid motion symmetry
N. E. Leonard and J. E. Marsden
Physica D, 105:103-162, 1997

97c/lmf97-cdc
Stabilization of Integrator Chains in the Presence of Magnitude and Rate Saturations: A Gain Scheduling Approach
Trygve Lauvdal, Richard M. Murray, Thor I. Fossen
1997 Conference on Decision and Control

97c/km97-rmp
The Hamiltonian and Lagrangian approaches to the dynamics of nonholonomic systems
W. S. Koon and J. E. Marsden
Reports on Mathematical Physics, 1997

97a/km97-jco
Optimal control for holonomic and nonholonomic mechanical
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SIAM Journal of Control and Optimization, 35:901-929, 1997

96r/tkm97-acc

Uniting local and global controllers for the Caltech ducted fan
Andrew R. Teel, Oliver Kaiser, Richard M. Murray
1997 American Control Conference

96o/nm96-jgcd
Rapid Hover to Forward Flight Transitions for a Thrust Vectored Aircraft
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Fast Mode Switching for a Thrust Vectored Aircraft
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Robust Nonlinear Control Theory with Applications to Aerospace Vehicles
John C. Doyle and Richard M. Murray
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96a/blp96-jgcd
Optimally scaled H_∞ full information control with real uncertainty: Theory and application
G. Balas, R. Lind and A. Packard
J. Guidance, Navigation and Control

96a/bhsm96-ifac
On Measures of Non-Integrability of Pfaffian Systems
Andrjez Banaszuk, John Hauser, Willem Sluis, Richard M. Murray
IFAC World Congress, July 1996

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A Homotopy Algorithm for Approximating Geometric Distributions by Integrable Systems
Willem M. Sluis, Andzrej Banaszuk, John Hauser, Richard M. Murray
System and Control Letters, 27: (5) 285-291, 1996

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Numerically Efficient Robustness Analysis of Trajectory Tracking for Nonlinear Systems
J. E. Tierno, R. M. Murray, J. C. Doyle, I. M. Gregory
J. Guidance, Control, and Dynamics, 20(4):640-647, 1997
CDS Technical Report CDS 95-032

95e/tm95-cdc
Robust Performance Analysis for a Class of Uncertain Nonlinear Systems
J. E. Tierno, R. M. Murray

Richard M. Murray (murray@cds.caltech.edu)

PRET Transition Database

These are some of the documented transitions within the PRET program. Transitions are listed in chronological order. You may also search this database by keyword.

- 3M, 1996
- MUSYN Inc. and the Naval Air Warfare Center, Patuxent River, MD., 1996
- American Control Conference, 1997
- MUSYN Inc. and the Naval Air Warfare Center, Patuxent River, MD, 1997
- Boeing North American, 1997
- Jet Propulsion Laboratory, 1998
- MUSYN Inc. and NASA Langley Research Center, 1998
- MUSYN Inc, Johns Hopkins Applied Physics Laboratory, 1998
- Boeing North American, 1998
- Jet Propulsion Laboratory, 1999
- MUSYN Inc. and NASA Langley Research Center, 1999
- MUSYN Inc, Johns Hopkins Applied Physics Laboratory, 1999
- United Technologies Research Center, 1999
- United Technologies Research Center, 2000
- MUSYN Inc., Lockheed Martin Aero, NASA Langley, 2000

Performer:	Prof Gary Balas, University of Minnesota, (612) 625-6857
Date:	1996
Customer:	3M
Contact:	Dr. Steve Mohn (612) 733-4639
Results:	Application of robust multivariable control analysis and design techniques to the control of extrusion processes.
Application:	Control design approach useful for the extrusion of thin films, composite ma- terials and other advanced material that requires numerous, actuators and sensors.

Performer:	Prof Gary Balas, University of Minnesota, (612) 625-6857
Date:	1996
Customer:	MUSYN Inc. and the Naval Air Warfare Center, Patuxent River, MD.
Contact:	Chris Mullaney, (301) 342-7720
Results:	Application of structured singular value synthesis technique via D-K iteration using the mu-Analysis and Synthesis Matlab Toolbox to the design of power-approach lateral-directional ight control law for the F-14. These control designs were compared with the newly developed digital flight control system (DFCS) which will be introduced into the fleet in the coming years. In piloted simulations of the power-approach landing, lead test pilot Lt. Scott Kelly of the DFCS flights, commented about the mu control design that "This is how I thought the airplane should fly. I thought it was the best flight control law I've own in the F-14. The AFCS has a lot of deficiencies, the DFCS is a big improvement over that, but in the limited look I had in

the simulator I really like what I saw of this design."

Application: The high performance, robust multivariable controllers significantly out performed the current designs. These results lend support to the use of advanced multi-variable control design techniques to design of current and future flight control systems. As systems become more highly coupled, robust multivariable techniques offer a major benefit over classical methods in terms of achievable performance, robustness and overall safety. The availability of commercial software (specifically the mu-Analysis and Synthesis Toolbox) provide industry and government labs usable advance control analysis and design tools.

Performer: Prof Gary Balas, University of Minnesota, (612) 625-6857

Date: 1997

Customer: American Control Conference

Contact: Dr. Mike Masten, (972) 995-7986

Results: A short course at the 1997 American Controls Conference on parameter-dependent control and its application to real world control problems (Co-Organizer with Prof. Andy Packard). This course provided attendees with a brief background on robust control, and linear matrix inequalities (LMIs). The underlining theory for LPV systems was presented as well as the solution to several gain-scheduled control problems that arise in the LPV framework. To provide hands-on experience analyzing and synthesizing controllers using linear parameter varying (LPV) techniques, we provided one PC computer for every 3 attendees. We have found this helped reinforce the theory and results presented in the lectures. A total of 55 people from a variety of areas attended this course. This was nearly twice the number of attendees than the other short courses.

Application: Application of LPV methods to the F-14 lateral-directional axis powered-approach ight control system, design of missile autopilots, a chemical process and turbofan engines were presented.

Performer: Prof Gary Balas, University of Minnesota, (612) 625-6857

Date: 1997

Customer: MUSYN Inc. and the Naval Air Warfare Center, Patuxent River, MD

Contact: Chris Mullaney, (301) 342-7720

Results: Application of LPV techniques to the design of power-approach lateral-directional flight control law for the F-14. These control designs were compared with the newly developed digital flight control system (DFCS) which will be introduced into the fleet in the coming years. In piloted simulations of the powered-approach landing, lead test pilot Lt. Scott Kelly and Lt. Poindexter of the DFCS ights, gave the LPV gain-scheduled designs a Cooper-Harper rating of 4. We have redesigned these LPV controllers and are waiting for an opportunity to test them in pilot-in-the-loop simulation.

Application: The high performance, robust, gain-scheduled multivariable controllers per- form as well as the current designs. These results lend support to these techniques to design current and future flight control systems. As systems become more highly coupled, robust, gain-scheduled multivariable techniques offer a major benefit over classical methods in terms of achievable performance, robustness and overall safety. LPV software will soon be available in commercial software (specifically the mu-Analysis and Synthe-sis Toolbox) provide industry and government labs usable advance control analysis and design tools.

Performer: Richard M. Murray, California Institute of Technology, (626) 395-6460

Date: 1997

Customer: Boeing North American

Contact: Daniel Hill, (714) 762-1151

Results: A collaborative project has been established between Boeing North American (formerly Rockwell) and Caltech to apply modern robust control techniques to stabilization of an electrostatic gyro and to evaluate performance enhancements due to use of mod- ern, multi-variable control techniques. Boeing has committed internal funds for FY97 and FY98 to provide technical support and experimental facilities. Initial meetings have been conducted to establish the overall direction of the collaboration and a student has been identified to work on the project. This work is jointly supported by the AFOSR PRET center the AFOSR MURI center on Robust Virtual Engineering.

Application: Application: High performance control of an electrostatic gyro, an inertial guidance sensor marketed by Boeing and currently used for ship and submarine applications.

Performer: Prof Jerrold Marsden, CDS, Caltech; marsden@cds.caltech.edu

Date: 1998

Customer: Jet Prcpulsion Laboratory

Contact: Dr. Martin Lo, mwl@trantor.Jpl.Nasa.Gov

Results: A partially supported AFOSR postdoc, Wang-Sang Koon, in collaboration with Jerrold Marsden and Martin Lo, discovered numerically an important heteroclinic connection in the three body problem. This heteroclinic connection (in the sense of dynamical systems) is between two halo orbits with the same Jacobi constant; one is around the libration point L1 and the other around L2. In solar system dynamics such as the Earth-Sun system, these orbits are widely separated (by several diameters of the moon's orbit). This connection will lead to a deeper understanding of the important phenomenon of resonant transitions (studied by, eg, Belbruno and B. Marsden) between the inner and outer Hill's region.

Application: This connection is important in the computation of the dynamics of specific missions such as the upcoming Genesis mission as well as the planning of future missions (eg, to Europa) and for the understanding of phenomena that are important in astrodynamics such as the capture of comets and asteroid impacts.

Performer: Prof Gary Balas, University of Minnesota, (612) 625-6857

Date: 1998

Customer: MUSYN Inc. and NASA Langley Research Center

Contact: Dr. Chris Belcastro, 757.864.4035

Results: Application of LPV techniques to the design of the longitudinal axis of the NASA High Speed Civil Transport (HSCT). The difficulty is that the HSCT is an extremely flexible aircraft which will require the active attenuation of flexible body modes as well as a standard flight controller. The LPV control designs will be compared with the current Boeing flight controller and augmented structural mode control system. The LPV designs will be tested in pilot-in-the-loop simulation at NASA Langley and NASA Dryden.

Application: The robust, gain-scheduled multivariable controllers perform as well as the current designs. These results lend support to these techniques to design current and future flight control systems. As systems become more highly coupled, robust, gain-scheduled multivariable techniques offer a major benefit over classical methods in terms of achievable performance, robustness and overall safety.

Performer: Prof Gary Balas, University of Minnesota, (612) 625-6857

Date: 1998

Customer: MUSYN Inc, Johns Hopkins Applied Physics Laboratory

Contact: Tom Urban, 240.228.7605

Results: Application of LPV techniques to the design of aggressive, high performance missile autopilots. The objective is to fly the missile at higher angles-of-attack and sideslip than previously possible with standard techniques. We have successfully synthesized autopilots for aggressive acceleration maneuvers at high mach numbers.

Application: Future missile systems and unmanned air vehicle can expand their operating range with these advanced, gain-scheduled multivariable techniques. In addition, the automated nature of these dynamics will minimize the time between design cycles.

Performer: Richard M. Murray, California Institute of Technology, (626) 395-6460

Date: 1998

Customer: Boeing North American

Contact: Daniel Hill, (714) 762-1151

Results: Results: A collaborative project has been established between Boeing North American (formerly Rockwell) and Caltech to apply modern robust control techniques to stabilization of an electrostatic gyro (ESG) and to evaluate performance enhancements due to use of modern, multi-variable control techniques. A control law has been designed and implemented on the ESG using a PC-based real-time control system. Robust analysis tools have been used to estimate the achievable performance and these results are being compared to alternative navigation technologies.

Application: High performance control of an electrostatic gyro, an inertial guidance sensor marketed by Boeing and currently used for ship and submarine applications.

Performer: Prof Jerrold Marsden, CDS, Caltech; marsden@cds.caltech.edu

Date: 1999

Customer: Jet Propulsion Laboratory

Contact: Dr. Martin Lo, mwl@trantor.Jpl.Nasa.Gov

Results: A prior partially supported AFOSR postdoc, Wang-Sang Koon in collaboration with Jerrold Marsden, Shane Ross and Martin Lo, building on their recently discovered heteroclinic connection in the three body problem have applied the ideas to the design of some new mission trajectories beyond the now well known Genesis trajectory.

Application: These new trajectories are to a \petit grand tour" of the moons of Jupiter. These new dynamical systems techniques allow one to create orbits that require only half the fuel of the traditional Hohmann transfer methods.

Performer: Prof Gary Balas, University of Minnesota Telephone 612.625.6857

Date: 1999

Customer: MUSYN Inc. and NASA Langley Research Center

Contact: Dr. Chris Belcastro, 757.864.4035

Results: Application of LPV techniques to the design of the longitudinal axis of the NASA High Speed Civil Transport (HSCT). The difficulty is that the HSCT is an extremely exible aircraft which will require the active attenuation of flexible body modes as well as a standard flight controller. The LPV control designs will be compared with the current Boeing flight controller and augmented structural mode control system. The LPV de- signs will be tested in pilot-in-the-loop simulation at NASA Langley and NASA Dryden.

Application: The robust, gain-scheduled multivariable controllers perform as well as the current designs. These results lend support to these techniques to design current and future flight control systems. As systems become more highly coupled, robust, gain-scheduled multivariable techniques offer a major benefit over classical methods in terms of achievable performance, robustness and overall safety.

Performer: Prof Gary Balas, University of Minnesota, (612) 625-6857

Date: 1999

Customer: MUSYN Inc, Johns Hopkins Applied Physics Laboratory

Contact: Tom Urban, 240.228.7605

Results: Application of LPV techniques to the design of aggressive, high per- formance missile autopilots. The objective is to fly the missile at higher angles-of-attack and sideslip than previously possible with standard techniques. We have successfully synthesized autopilots for aggressive acceleration maneuvers at high mach numbers.

Application: Future missile systems and unmanned air vehicle can expand their operating range with these advanced, gain-scheduled multivariable techniques. In addition, the automated nature of these dynamics will minimize the time between design cycles.

Performer:	Richard M. Murray, Caltech, murray@indra.caltech.edu
Date:	1999
Customer:	United Technologies Research Center
Contact:	Robert Hobbs, (860) 610-7421
Results:	Murray hired by UTRC as Director, Mechatronics Systems. Effective 7/1/98.
Application:	Nonlinear dynamics and control problems in gas turbine engines (Pratt & Whitney), rotorcraft and UAVs (Sikorsky), HVAC/R (Carrier), and elevators (Otis).

Performer:	Richard M. Murray, Caltech, murray@indra.caltech.edu
Date:	2000
Customer:	United Technologies Research Center
Contact:	Robert Hobbs, (860) 610-7421
Results:	Murray worked at UTRC as Director, Mechatronics Systems through 15 March 2000.
Application:	Nonlinear dynamics and control problems in gas turbine engines (Pratt & Whitney), rotorcraft and UAVs (Sikorsky), HVAC/R (Carrier), and elevators (Otis).

Performer:	Prof Gary Balas, University of Minnesota, 612.625.6857
Date:	2000
Customer:	MUSYN Inc., Lockheed Martin Aero, NASA Langley
Contact:	Dr. Christine Belcastro 757.864.4035, Dr. Rowena Eber-
Results:	Synthesize a ight controller for the Gulfstream V using the LPV techniques developed under the AFOSR PRET program as part of the NASA Aviation Safety Control and Upset Management Program. This work is being performed under the Lockheed-Martin AIMSAFE program.
Application:	NASA and Lockheed-Martin view parameter dependent system theory as a potential unifying approach to on-line health monitoring and identification, fault detection, reconfiguration or adaptation and flight control.